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ScienceDirect
Procedia Engineering 121 (2015) 1998 – 2005
Procedia Engineering
www.elsevier.com/locate/procedia

9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE)

Pressure Gradient Control and Energy-saving Operation Strategy Study on a Multi-zone Cleanroom

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Abstract

Pressure gradient control is an effective technical measure to prevent the external pollution and cross-contamination from different clean areas of a multi-zone cleanroom, which played a key role for the quality control of cleanroom. In this paper, modelling analysis combined with experimental investigations conducted on a multi-zone cleanroom experimental platform. A series of investigations were conducted on the experimental platform with supply air volume variation by electronic frequency conversion on air-supply fan unit. The characteristics of cleanroom such as cleanliness, ventilation rate, pressure gradient were all measured. An energy-saving operation strategy for multi-zone cleanroom has been gained. Experimental investigations proved that the determined principle of pressure gradient setting is feasible for reliable and energy-saving operation. It is also proved through experiments that about 24.5% energy consumption decreased when adopted the operation strategy.

Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015

Keywords: Multi-zone cleanroom; Pressure gradient; Energy-saving

1. Introduction

A high-performance cleanroom should provide efficient energy performance in addition to effective contamination control. The purpose of effective control of particle concentration in cleanroom with certain cleanliness level is achieved by maintaining sufficient magnitude and deviation of pressure between clean spaces

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Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015
doi:10.1016/j.proeng.2015.09.198

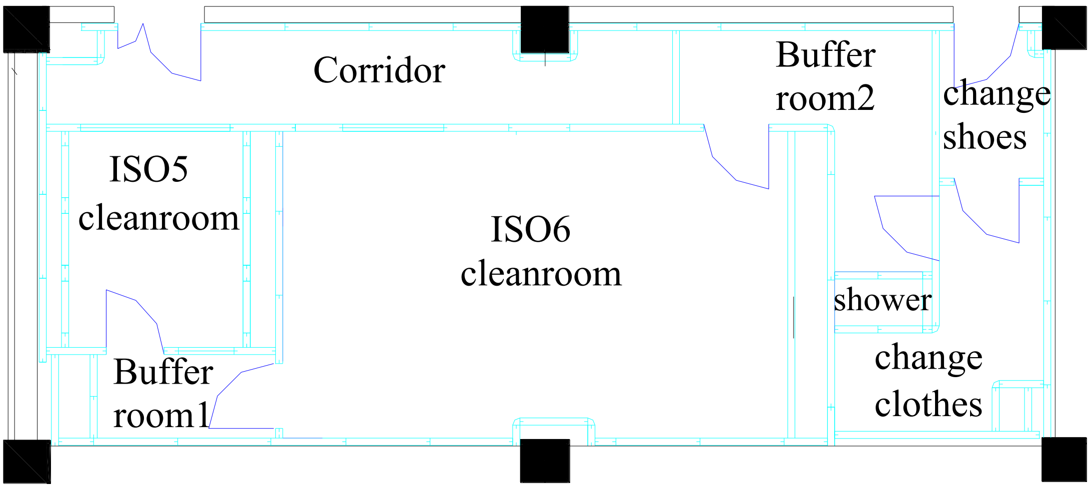
[1,2]. A reasonable pressure gradient can result in a defined airflow direction and decrease the risk of cross contamination.

Energy consumption is also focused in recent study on cleanroom. Cleanrooms, which can require high air changes per hour through High Efficiency Particulate Air (HEPA) filters to maintain certain cleanliness, are 30-50 times more energy intensive than a typical commercial building [3,4]. A past study of demand-controlled filtration [5] has shown 37-40% reductions in fan energy consumption when cleanroom fan speeds are modulated based on contaminant particle concentrations. It is also indicated that high, constant ventilation rates may be unnecessary for maintaining desired particle counts [6]. Since the energy consumption of a fan varies roughly as the cube of fan speed [7], the potential for energy savings in cleanrooms is commensurate with the magnitude of their energy consumption.

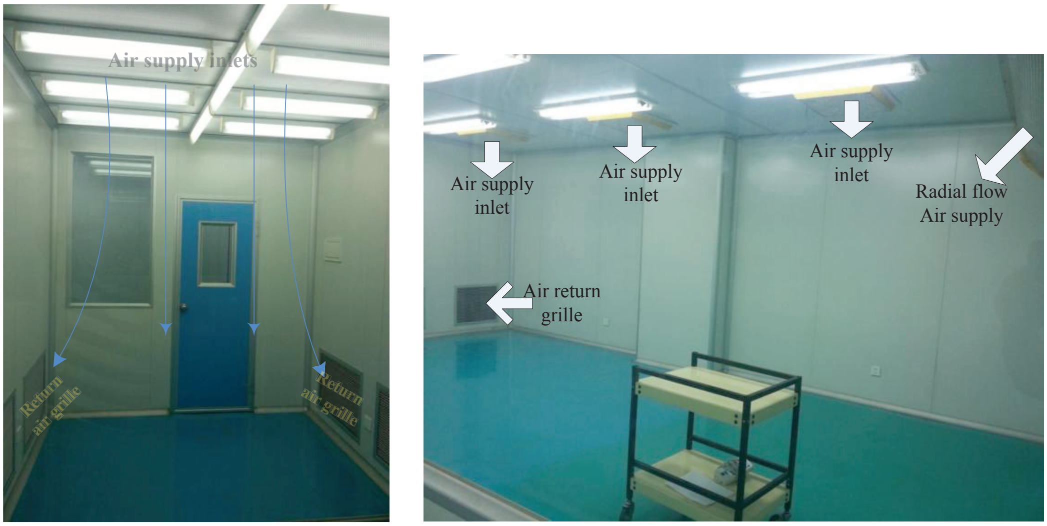
This paper explores opportunities to improve the energy efficiency of cleanrooms while maintaining desired cleanliness level.

2. Description of cleanroom investigated and measuring method

The laboratory chamber was set-up with typical arrangement for pharmaceutical manufacturing, operating rooms, as shown in Figure 1(a). In the clean space with ISO cleanliness class 5, filtered air is supplied from the ceiling equipped with fan-filter units (FFUs) to create qusi-unidirectional air flows and returned to the wall grilles that are vertical to the floor, as shown in Figure 1(b). Wall-return coupled with air-supply from ceiling without FFUs is designed and constructed to create non-unidirectional airflows in the clean space with ISO cleanliness class 6, two air-supply arrangements are employed in the ISO6 cleanroom: ceiling air-inlets and radial inlets at ceiling corner, as shown in Figure 1(c). The clean spaces such as corridor, dressing room (change shoes, change clothes) are designed as ISO cleanliness class 8, with the same ventilation arrangement as ISO6 cleanroom.



(a) plan view of the investigated multi-zone cleanroom chamber



(b) airflow arrangement in ISO5 room (c) airflow arrangement in ISO6 room

Fig 1. Full-scale laboratory chamber for multi-zone cleanroom operation strategy study

Air systems combine re-circulating air, make-up air (air handling), exhaust systems, regulating valves are set in the main air duct, and send air fan is configured with frequency variation unit, pressure differential between different clean spaces are well measured, as shown in Figure 2.

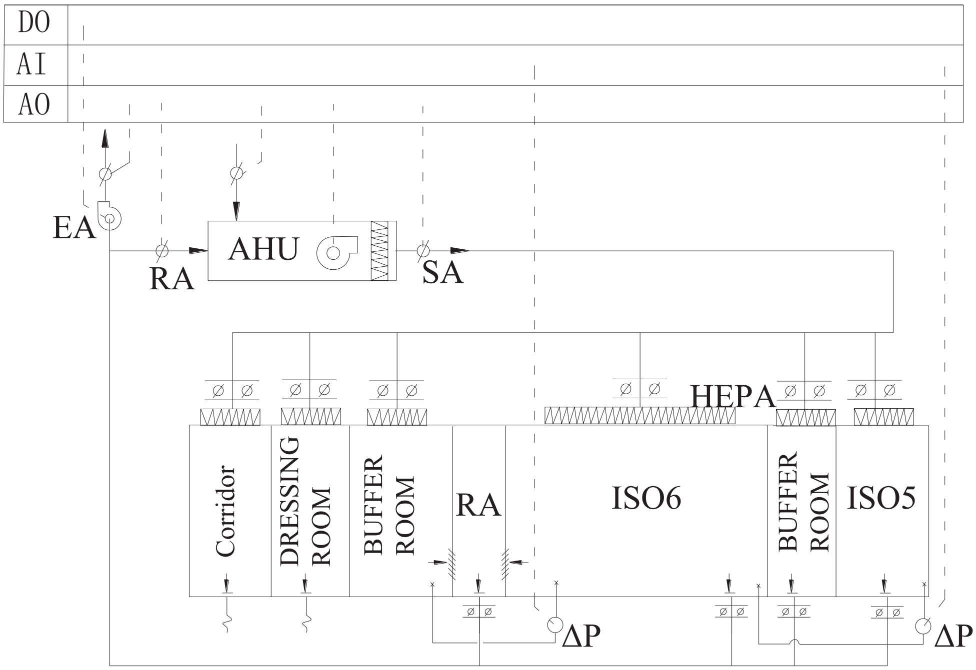


Fig 2. Schematic of airflow path in the cleanroom laboratory chamber

According to the design code for cleanroom and acceptance code for ventilation works, the measured parameters included airflow speed, static pressures, and particle concentrations in the clean space.

The measurement accuracy of airflow speed measurement device is ±1.5% under10.2m/s. Airflow rate device which is capable of measuring the range from 85~3400m3/h with measurement accuracy of ±3%, can be employed to measure air flow rate at air inlets. Air pressures were also measured using soft tubes with a multi-meter. The multi-meter is capable of measuring a wide range of air pressure from 0 to 3735Pa with measurement accuracy of ±1%. Laser particle counters were used to measure the particle concentration within the clean spaces. The laser-based particles counter discriminated and counted particles with sizes of 0.3,0.5,1.0,3.0,5.0,10.0μm. The airflow rate used for particle sampling was 1 cfm (28.3 l/min).

3. Analysis on multi-zone pressure gradient control

Multi-zone airflow network model predicts zone-to-zone airflows based on pressure-flow characteristics of the path models, and pressure differences across the paths. This model do not prescribe details of air flow in zones, each clean zone is characterized by a single pressure "node", then airflow relationships between different zones (or "nodes") is characterized by a series of "branches". These "branches" reflect that airflow rate from one zone to another is some function of the pressure difference along the flow path, for example, the function is commonly implemented as [8]:

$$Q = C(\Delta P)^n \tag{1}$$

Where, Q—volumetric airflow rate
C—flow coefficient
ΔP—pressure difference between different zones
n —flow exponent(typically 0.5)

According to the multi-zone airflow network model, the corresponding relationship between clean zones can be described as Figure 3. And the relationship between leakage airflow volume and pressure difference can be characterized as equation (2).

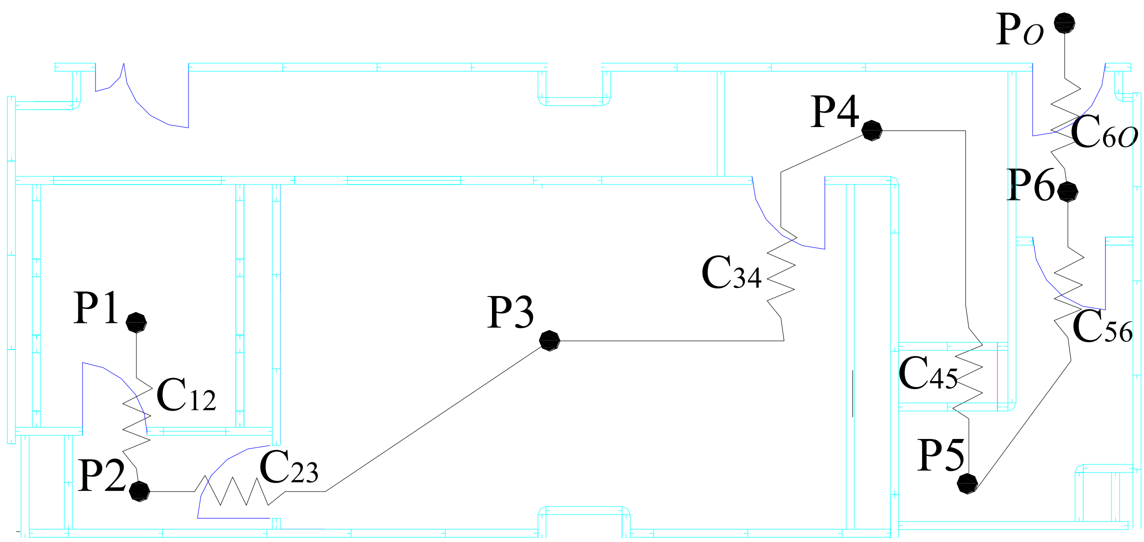


Fig 3. Airflow path model in the cleanroom laboratory chamber

$$\left.\begin{array}{l} C_{12}\sqrt{P_1-P_2}+Q_1=0 \\ C_{12}\sqrt{P_1-P_2}-C_{23}\sqrt{P_2-P_3}+Q_2=0 \\ C_{23}\sqrt{P_2-P_3}-C_{34}\sqrt{P_3-P_4}+Q_3=0 \\ C_{34}\sqrt{P_3-P_4}-C_{45}\sqrt{P_4-P_5}+Q_4=0 \\ C_{45}\sqrt{P_4-P_5}-C_{56}\sqrt{P_5-P_6}+Q_5=0 \\ C_{6O}\sqrt{P_6-P_O}-C_{56}\sqrt{P_5-P_6}+Q_6=0 \end{array}\right\} \quad (2)$$

Where, C_{ij} ——flow coefficient between zone i and zone j, i=1~5,j=2~6;
C_{6O} ——flow coefficient between change shoes zone and outdoor;
P_i ——characterized zone pressure ,i=1~6;
P_O ——outdoor pressure;
Q_i ——air supply to maintain pressure difference,
or leakage airflow volume, i=1~6.

Based on the analysis model described as equation (2), ventilation frequency corresponding the leakage airflow volume maintaining certain pressure difference were calculated respectively with 5Pa and 10 Pa pressure gradient, as shown in Figure 4. For a typical cleanroom, the ventilation frequency correspond to the leakage air flow volume ranges from 2 to 4 when 5Pa pressure gradient is maintained, and ranges from 3 to 6when 10Pa pressure gradient is maintained. It can be seen that ventilation frequency correspond to the leakage airflow volume in clean zone with large space volume such as ISO6 cleanroom is far lower than the recommended values, while clean zone with small space volume needs more leakage airflow volume maintaining sufficient pressure differential.

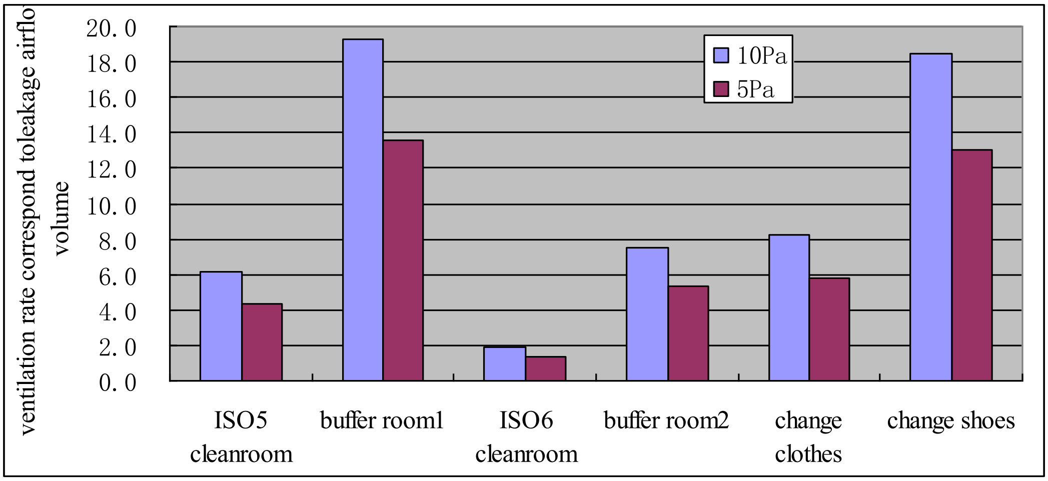


Fig 4. the ventilation frequency correspond to the leakage air flow volume to maintain certain pressure gradient

4. Energy-saving operation strategy and verification

Then a operation principles for multi-zone cleanroom can be considered as follows: appropriately increase the pressure gradient between clean zone at higher cleanliness level and its adjacent buffer room, reduce the pressure gradient between high clean zone adjacent buffer room and clean zone at lower cleanliness level; simultaneously increase the pressure gradient between clean zone and outdoor. Two aspects of improvement for efficiency operation can be achieved: one is to ensure protecting cleanrooms from contamination from outdoor, enhance the anti-disturbance ability of clean zone at higher cleanliness level; the other is to achieve energy saving on fan by reduce leakage airflow volume.

Taking the maintenance of cleanliness into account, sufficient ventilation rate correspond to air supply for dilution and replacement of containment are desired to achieve effective containment control. Combined with the operation principles mentioned above, the energy-saving operational strategy is gained: (1) according to multi-zone ventilation network model, leakage airflow volume can be determined with sufficient pressure gradient ; (2) according to cleanliness measured, airflow rate maintaining effective contaminant control is determined based on uneven distribution theory [9] combined with experimental analysis; (3) then desired air supply can be determined as setting parameter for frequency conversion control on air supply fan, associated with measured air-supply, reasonable working condition is under control. The control strategy diagram is shown in Figure 5.

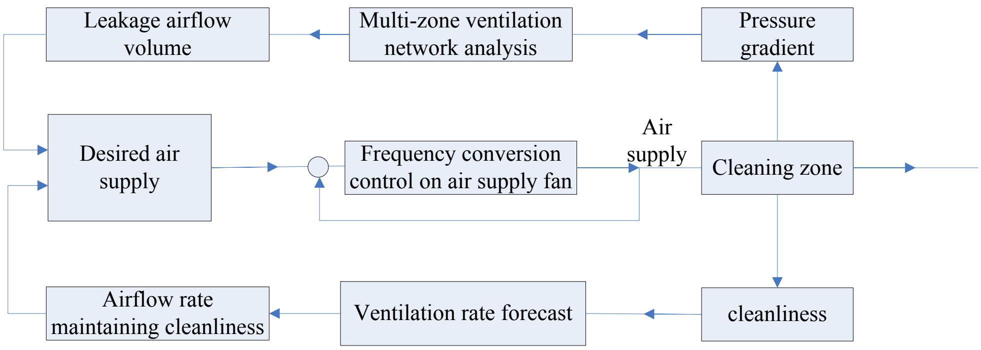


Fig 5. The diagram of operation control strategy

Figure 6 shows ventilation rate forecast and verification in ISO6 clean room. It indicates that 50 air changes in the clean zone is necessary to maintain ISO6 clean class. The air supply fan speed can be regulated between 45Hz to 50Hz.

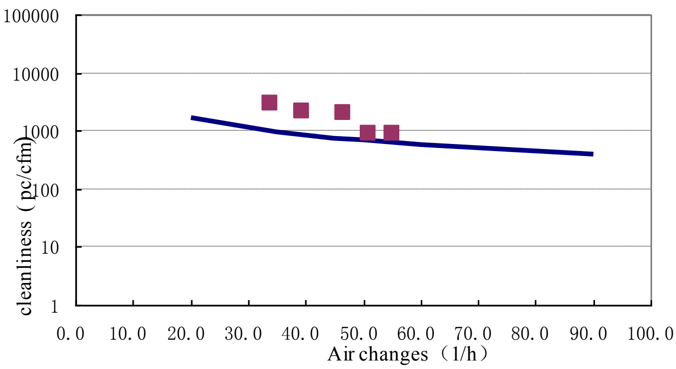


Fig 6. Ventilation rate forecast and verification in ISO6 cleanroom

Figure 7 shows pressure differential of different clean zones varied when the air supply fan speed was regulated from 50Hz to 45Hz. It can be seen the pressure gradient kept original trend, which indicates the stability of control process.

During the operation and control process, particle concentrations (>0.5μm) in ISO5 cleanroom are less than10; buffer room1 and buffer room2 can meet ISO6 cleanliness class, the clean zone for change clothes can meet ISO7 cleanliness class, as shown in Figure 8. It indicates that the operation strategy can achieve effective contaminant control.

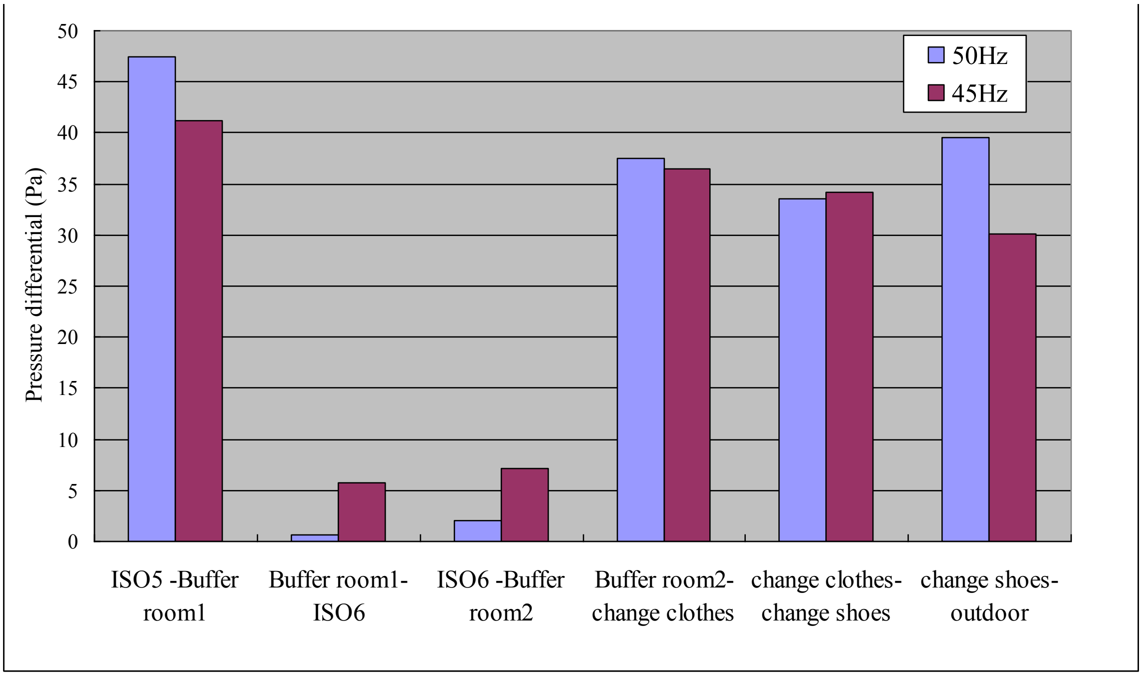


Fig 7. Pressure gradient variation with fan speed regulated from 50Hz to 45Hz

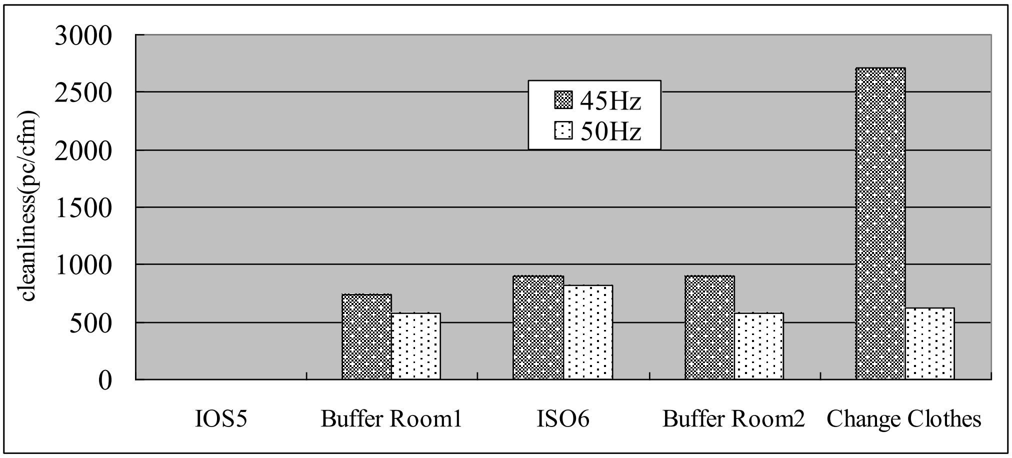


Fig 8. Particle concentration in different clean zones with air-supply fan speed regulated from 45Hz to 45Hz

Table 1 lists the main operation parameters of air-supply fan worked at 45Hz and 50Hz respectively. It can be determined that about 24.5% energy-saving is achieved when air-supply fan worked at 45Hz.

Table 1. Operation parameters of air-supply fan

f	Speed (rpm)	I(A)	U(V)
45Hz	1350	15.5	297.6
50Hz	1500	18.3	333.8

5. Conclusions

Based upon analyses, measurements and experimental verification, the following conclusions are drawn:

(1) the space volume of clean zone has significant influence on pressure gradient, it is necessary to set reasonable pressure differential according to the cleanroom volume; the considerable operation principle is that to reduce pressure gradient between clean zone with large space volume and its adjacent zones, and to increase pressure gradient between clean zone with small space volume and its adjacent zones;

(2) the effective operation strategy is established with the main control parameter of cleanliness and the auxiliary control parameter; multi-zone airflow network model combined with uneven distribution theory is used to determine desired air-supply as setting parameter for variable frequency speed regulation measure. Energy-saving operation achieved in addition to effective contamination control.

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